THE GASEOUS HALOES OF DISC GALAXIES

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Abstract

The study of gas outside the plane of disc galaxies is crucial to understanding the circulation of material within a galaxy and between galaxies and the intergalactic environment. We present new H I observations of the edge-on galaxy NGC 891, which show an extended halo component lagging behind the disc in rotation. We compare these results for NGC 891 with other detections of gaseous haloes. Finally, we present a dynamical model for the formation of extra-planar gas.

1. Introduction

Gas plays a vital role in the evolution of disc galaxies. The collapse of gas produces star formation; stars enrich gas, expel it via winds and supernova explosions and create a circulation called the galactic fountain (e.g. Shapiro & Field 1976). Outflows of gas from galactic discs with velocities of the order of 100 $\mathrm{km\,s^{-1}}$ are indeed observed both in the neutral (Kamphuis, Sancisi & van der Hulst 1991) and the ionised phase (Fraternali, Oosterloo & Sancisi 2004). On the other hand, disc galaxies also seem to acquire a substantial amount of gas from their surroundings. Accretion of unpolluted material from the Intergalactic Medium (IGM) is predicted by chemical evolution models of the Milky Way (e.g. Rocha-Pinto & Maciel 1996) and the low metallicities of some of the High Velocity Clouds (HVCs) (e.g. Tripp et al. 2003) suggest that cold material is indeed accreted by spiral galaxies like our own (Oort 1970).

In recent years, a new and important fact has emerged. Observations at various wavelengths have shown the presence of a considerable amount of gas in the haloes of disc galaxies (extra-planar or halo gas). Deep Hα observations

have revealed the presence of extended layers of diffuse ionised gas (DIG) around edge-on spiral galaxies (Hoopes, Walterbos & Rand 1999). X-ray observations have shown the presence of hot plasma at distances of tens of kpc from the plane of galactic discs (e.g. Strickland et al. 2004). H I observations have revealed extended thick layers surrounding the galactic discs (Swaters, Sancisi & van der Hulst 1997; Fraternali et al. 2001; Matthews & Wood 2003). The origin and the nature of this halo gas are still unknown. However, it is a unique probe to study the exchange of gas within a galaxy and between galaxies and the IGM.

2. NGC 891

NGC 891 is one of the best known and studied nearby edge-on galaxies. It is at the distance of 9.5 Mpc, classified as a Sb/SBb, and it is often referred to as very similar to the Milky Way (e.g. van der Kruit 1981).

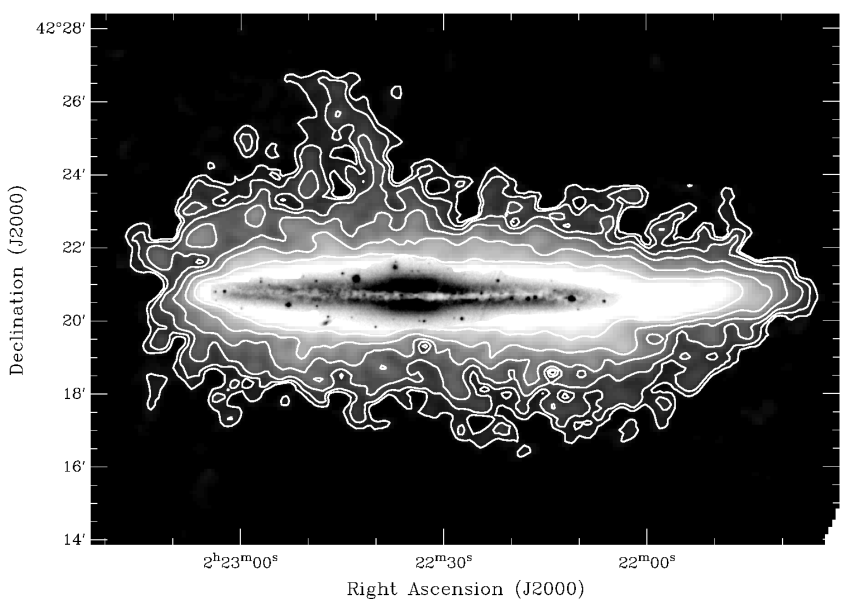

Figure 1. Optical DSS image (grey-scale) and total H I map (contours+negative grey-scale) of NGC 891, the latter obtained from the new WSRT observations (Oosterloo, Fraternali & Sancisi 2005). H I contours are: 1.7, 4.5, 9, 18.5, 37, 74, 148, 296.5, 593 $\times\ 10^{19}$ atoms cm^{-2}. The beam size is 28″; 1′ =2.8 kpc.

NGC 891 has been the subject of numerous studies at different wavelengths that have led to the detection of various halo components: an extended radio halo (Allen, Sancisi & Baldwin 1978), a thick layer of diffuse ionised gas (DIG) (e.g. Dettmar 1990), and diffuse extra-planar hot gas (Bregman & Pildis

1994). Also "cold" ISM components have been detected in the halo such as H I (Swaters, Sancisi & van der Hulst 1997), dust (Howk & Savage 1999) and CO (Garcia-Burillo et al. 1992).

New H I observations of NGC 891 have been obtained with the Westerbork Synthesis Radio Telescope (WSRT) with a total integration time of about 200 hrs (Oosterloo, Fraternali & Sancisi 2005). Fig. 1 shows the new total H I map of NGC 891 in contours overlaid on a grey-scale DSS optical image. This H I halo is remarkably extended with a spur of gas reaching a distance of 15 kpc from the plane. The H I disc of NGC 891 is lop-sided, more extended on the S-W side of the galaxy (right in Fig. 1) and possibly *truncated* on the N-E (left) side (see also Sancisi & Allen 1979; Swaters, Sancisi & van der Hulst 1997).

The halo gas in NGC 891 rotates more slowly than the gas in the plane (Swaters, Sancisi & van der Hulst 1997). This is a common property of gaseous haloes (e.g. Fraternali et al. 2001; Heald et al. 2005a). Our new data allow us to study the kinematics of the halo gas in detail and derive rotation curves at different heights from the plane (Fraternali et al. 2005; Fraternali, in preparation). The measured gradient in rotation velocity is $\Delta_{\mathrm{v_{rot}}} \sim -15\,\mathrm{km\,s^{-1}kpc^{-1}}$ for $1.3<z<5.2$ kpc. This value agrees with the velocity gradient measured in the ionised gas (Heald et al. 2005b).

3. Halo gas in other disc galaxies

How common are gaseous haloes? Until now, neutral extra-planar gas has been studied in 6 disc galaxies. The H I data for these galaxies are among the deepest ever obtained and this may indicate that halo gas is a common feature that has escaped detection because of a lack of sensitivity.

Table 1. Observations of halo gas in disc galaxies

Galaxy	Type	Distance (Mpc)	M_{halo} H I ($10^8\ M_\odot$)	$M_{\mathrm{halo}}/M_{\mathrm{total}}$ (%)	L(FIR) ($L_\odot$)	Ref.
NGC 253	Sc	3.9	0.8	3	2.63×10^{10}	1
NGC 891	SBb	9.5	6	15	1.25×10^{10}	2
NGC 6946	Scd	6.0	>3.5	>5.8	9.79×10^{9}	3
NGC 4559	Scd	9.7	5.9	11.5	1.91×10^{9}	4
NGC 2403	Scd	3.2	3	11.0	1.13×10^{9}	5
UGC 7321	Sd	10.0	$\gtrsim 0.1$	$\gtrsim 1$	7×10^{7}	6

[1] Boomsma et al. 2005a; [2] Swaters, Sancisi & van der Hulst 1997; [3] Boomsma et al. 2005b; [4] Barbieri et al. 2005; [5] Fraternali et al. 2002; [6] Matthews & Wood 2003.

Table 1 summarizes the 6 halo gas detections sorted by their FIR luminosity (which is a measure of the star formation rate, SFR). A relation between the amount of halo gas and the SFR may be expected if the halo gas has a galactic

fountain origin. It is possible that a trend is indeed present for low luminosity galaxies. Note that the mass of halo gas estimated for NGC 6946 is a lower limit due to the low inclination ($\sim 30°$) of the galaxy that does not allow an efficient separation of the halo component (Boomsma et al. 2005b). However, the starburst galaxy NGC 253 is totally anomalous, having very little extra-planar H I compared to the other galaxies. This may be an indication that in the most actively star forming galaxies most of the halo gas is ionised.

In addition to these galaxies, there are indications of the presence of halo gas in several others (e.g. NGC 5055, Battaglia et al. 2005; UGC 1281, Kamphuis et al., this conference; UGC 12632, Oosterloo, private communication) and extra-planar features have been observed in NGC 2613 (Chaves & Irwin 2001). Moreover, it is very likely that this halo gas is analogous to the Intermediate and High Velocity Clouds (IVCs/HVCs) of the Milky Way (Wakker & van Woerden 1997) and of external galaxies (M31 and M33, Westmeier, Braun & Thilker; M83 and M51, Miller & Bregman 2005).

4. A dynamical model for extra-planar gas

What is the origin of these gaseous haloes? Some authors have tried to explain them using ballistic galactic fountain models and compared them with Hα observations of ionised gas (Collins, Benjamin & Rand 2002; Heald et al. 2005a). They found a general disagreement between the kinematics and distribution of the halo gas predicted by the models and those shown by the data. Other authors have tried to model the halo gas as a stationary medium in hydrostatic equilibrium (Benjamin 2002; Barnabe' et al. 2005). This approach leads to solutions that can reproduce the observed gradient in the rotation velocity (Barnabe' et al. 2005), however the temperatures of the extra-planar (hydrostatic) gas are of the order of 10^5 K and it is unclear how this medium can be related to cold neutral gas.

We have developed a model for the formation of the neutral extra-planar gas that takes into account internal and external processes. At the current stage (Fraternali & Binney 2005) the model tries to reproduce the halo gas as a continuous flow of collision-less particles from the disc into the halo region. The particles are stopped at the passage through the plane. The output of the models are particle-cubes that can be directly compared to the H I data-cubes. The idea behind this approach is to start from a basic model, study its failures and improve it progressively to match the data more and more closely.

Figure 2 shows three representative channel maps of NGC 891 (left column) compared with those produced by two dynamical models. The two models are for maximum and minimum disc (maximum DM halo) potentials. The channel maps shown here have velocities far from systemic i.e. they show the gas that rotates the fastest. The data show that this gas is mostly located in the disc (the

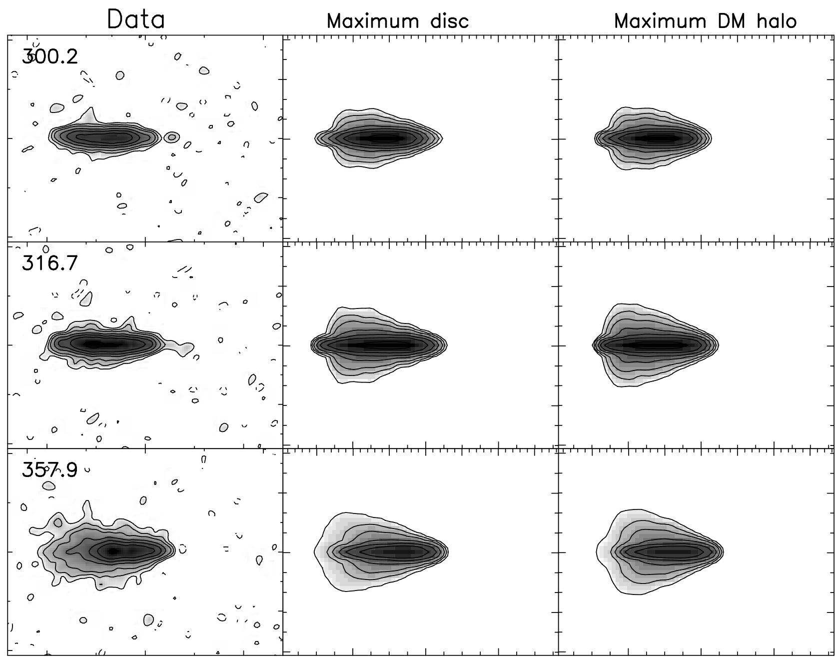

Figure 2. Comparison between three observed channel maps of NGC 891 (Oosterloo, Fraternali & Sancisi 2005) and those produced with the two dynamical models. The first column shows the data, heliocentric radial velocities are reported in the upper left corner.

channel maps are thin) whilst the models predict much thicker channel maps, i.e. fast rotating extra-planar gas. This is a failure of the fountain model and this problem cannot be removed by allowing the particles to cross the disc or by considering that they are ionised as they leave the plane and become visible at 21 cm at some point on their orbits (phase change). There is an intrinsic and unavoidable need for low angular momentum material, which suggests that one has to take into account interactions between the fountain flow and a hot gaseous halo and/or accretion material (Fraternali & Binney, in preparation).

5. Conclusions

The new H I observations of NGC 891 show the presence of extended neutral gas halo reaching up the distance of 15 kpc from the plane. This halo gas rotates more slowly than the gas in the plane (with a gradient of −15 km $s^{-1}kpc^{-1}$). These kinematic properties cannot be explained by an isolated galactic fountain; they require that interactions with a hot halo and/or gas accretion from the IGM must play an important role.

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